

UNCLASSIFIED

AD NUMBER
AD000378
NEW LIMITATION CHANGE
TO Approved for public release, distribution unlimited
FROM Distribution authorized to DoD only; Test and Evaluation; AUG 1952. Other requests shall be referred to Office of Naval Research, Arlington, VA 22203. Pre-dates formal DoD distribution statements. Treat as DoD only.
AUTHORITY
ONR ltr dtd 26 Oct 1977

THIS PAGE IS UNCLASSIFIED

Reproduced by

Armed Services Technical Information Agency DOCUMENT SERVICE CENTER

KNOTT BUILDING, DAYTON, 2, OHIO

AD -

3 7 8

UNCLASSIFIED

BENDING BUCKLING TESTS OF SANDWICH CYLINDERS

George Gerard

College of Engineering
New York University



Sponsored by Office of Naval Research under
Contract No. N6-onr-279 Task Order V.

August 1952

Introduction

As part of a program involving a theoretical and experimental study of the buckling behavior of sandwich cylinders, this report is concerned with buckling tests of thin and thick walled sandwich cylinders under bending loads. Tests were conducted on cylinders constructed with cores weak in shear (cellular cellulose acetate) and cores strong in shear (end grain balsa) to check the validity of theoretical procedures for predicting overall buckling and wrinkling of sandwich cylinders under bending loads.

TEST PROGRAM

Test Specimens

The large number of variables which influence the behavior of a composite element such as sandwich construction require that in a test program attention be directed toward the significant parameters only. Thus, in order to study the overall buckling characteristics of sandwich cylinders, it is necessary that the sandwich thickness be as small as possible. The 1/8 inch thick sandwich used was considered to be the minimum thickness feasible. To study the wrinkling behavior of cylinders under bending loads a 1/2 inch thick sandwich was used. The nominal radius of 6 inches which was used for all cylinders was dictated by the capacity of the testing facilities. To ensure uniformity of introduction of bending load, the cylinders tested were 36 inches long.

The significant parameter in overall buckling of sandwich elements is the shear rigidity of the core material whereas the transverse elastic modulus of the core is the important parameter in wrinkling. Consequently, two different materials were selected for the core: cellular cellulose acetate (CCA) of approximately 6 lbs./cu.ft. density and end grain balsa (EGB) of approximately 5 to 5.5 lbs./cu.ft. density. For all cylinders, the face material used was 0.010 inch 24S-T3 aluminum alloy.

The cylinders used in this investigation were manufactured by Skydyne Inc. of Port Jervis, New York. The fabrication details were briefly as follows. The aluminum alloy faces were coated with a metal primer prior to assembly to the core. The core was planed

to the proper thickness and a secondary adhesive was used to bond the faces to the core. Although the adhesive used will polymerize at room temperature, sufficient heat was applied to accelerate setting of the adhesive. Pressure necessary to bring the surfaces in intimate contact was applied and the assembly was molded for a period of 2 to 3 hours.

To facilitate installation of the test specimen in the loading jig, two inch wide hardwood blocks were bonded to both the inside and outside faces at each end of the cylinder (see Figs. 1 and 3). The end faces of these blocks were then turned down on a lathe to insure planeness of the face, perpendicularity with the axis of the cylinder and parallelism of the faces.

Test Procedure

The pertinent dimensions of each specimen were determined as follows. Four evenly spaced longitudinal stations were lightly scribed on the outside wall of the cylinder. The outside radius was then measured to the nearest 0.01 inch at each pair of stations at both ends. The length of the cylinder between hardwood blocks was also determined at each station to the nearest 0.01 inch.

The total thickness of the cylinder wall was measured at each station at both ends just inside the hardwood blocks and at the center by means of a special dial gage with a least division of 0.001 inch. The thickness of the faces was measured with a ten-thousandths micrometer on samples of the face material. The average dimensions for each cylinder are given in Table 1.

Installation of the specimens in the specially designed bending loading jig was accomplished by bolting the specimen to the steel end plates through the hardwood blocks at the ends of the cylinder. The loading jig is shown in Fig. 1 with a specimen installed and tested. Load was applied by means of a hydraulic tension jack and was measured by a calibrated strain gage tension link at the jack which was accurate to ± 2 percent.

Physical Property Tests

The important physical properties in overall bending buckling of sandwich construction are the compressive stress-strain characteristics of the face material and the shear modulus of the core material. For wrinkling, the important properties are the compressive elastic moduli in each of the three planes of the core and the face characteristics.

The shear moduli of the core materials were determined by testing as simple beams, strips of flat sandwich construction. The beams were fabricated by the manufacturer of the cylinders of the same materials and in the same manner as the cylinders themselves. The test consisted of obtaining load-deflection data from which the shear modulus of the core material was determined from the difference in deflection between the experimental value and that computed for the beam neglecting shear deflections. From at least four tests of each core material, the following values of shear modulus were obtained:

cellular cellulose acetate: $\bar{G} = 3400 \text{ psi} \pm 17\%$

end grain balsa: $\bar{G} = 17,600 \text{ psi} \pm 15\%$

The compressive elastic moduli of the core was measured on 1" x 2" x 2" blocks of core material. From at least 8 tests in the direction perpendicular to the faces and 4 tests in the other two directions the values of elastic compressive moduli were as follows:

cellular cellulose acetate (CCA):

$$\bar{E}_z = 10,500 \text{ psi} \pm 16\% \text{ (perpendicular to faces)}$$

$$\bar{E}_1 = 17,700 \text{ psi} \pm 18\% \text{ (extrusion direction)}$$

$$\bar{E}_2 = 3,600 \text{ psi} \pm 25\% \text{ (transverse to extrusion direction)}$$

and grain balsa (EGB):

$$\bar{E}_z = 86,000 \text{ psi} \pm 12\% \text{ (perpendicular to faces)}$$

$$\bar{E}_1 = 14,400 \text{ psi} \pm 40\% \text{ (radial direction)}$$

$$\bar{E}_2 = 4,500 \text{ psi} \pm 20\% \text{ (circumferential direction)}$$

It is to be noted that according to data given in Ref. 1, the value of \bar{E}_z of 86,000 psi appears to be considerably lower than given therein. However, the value of \bar{E}_z obtained did correspond to that given for quipo wood which is closely related to balsa. In addition, the material tested here closely followed the description of quipo wood given in Ref. 1 as well as certain other strength characteristics. Thus, it is suspected that the core material used in the sandwich cylinders was actually quipo rather than balsa.

The with grain compressive stress-strain characteristics of the 0.010 in. 24S-T3 aluminum alloy used for the faces of the sandwich cylinders was determined by use of a solid guide compression jig of the National Bureau of Standards type. The stress-strain data are shown in Fig. 2.

Test Results

Average measured dimensions of the sandwich cylinders together with the failing loads are given in Table 1. Photographs of typical buckle patterns taken after the conclusion of the tests are shown for each type of cylinder; Fig. 3 shows a typical overall buckle pattern obtained on most of the $1/8$ in. cylinders, Fig. 4 shows a typical wrinkle for the $1/2$ in. end grain balsa cylinders and Fig. 5 shows a typical wrinkle for the $1/2$ in. cellular cellulose acetate cylinders. Additional data on the buckling and wrinkling patterns are given in Table 2. The measured wavelengths were obtained in regions of relatively little distortion.

TABLE I

Average Dimensions and Failing Loads of Sandwich Cylinders

Cylinder	Core Material	Length	Mean Radius	Total Thickness	Average Face Thickness	Failing Moment	Maximum Failing Load/In.	Maximum Failing Stress
		L	R	($\bar{h} + t$)	t	M_{cr}	$N_{cr} = M_{cr}/R^2$	σ_{cr}
-1	CCA	32.09"	6.48"	0.141"	0.0105"	67,900"lbs.	514 lb/in.	19,300 psi
-2	CCA	32.13	6.50	0.125	0.0105	46,100	347	16,500
-3	CCA	32.13	6.49	0.125	0.0105	77,700	587	28,000
-4	CCA	32.16	6.53	0.141	0.0105	89,600	670	31,900
-5	CCA	32.16	6.20	0.532	0.0105	92,400	764	36,400
-6	CCA	32.25	6.18	0.500	0.0105	77,700	648	30,900
-7	EGB	31.29	6.47	0.141	0.0105	53,100	404	19,300
-8	EGB	31.09	6.55	0.156	0.0105	65,700	500	23,800
-9	EGB	32.16	6.69	0.515	0.0105	82,500	588	28,000
-10	EGB	32.25	6.69	0.515	0.0105	113,300	807	38,500

BENDING BUCKLING TESTS OF SANDWICH CYLINDERS

George Gerard

College of Engineering
New York University

Sponsored by

Office of Naval Research
under Contract N6-onr-279, Task Order V.

August 21, 1952

Introduction

As part of a program involving a theoretical and experimental study of the buckling behavior of sandwich cylinders, this report is concerned with buckling tests of thin and thick walled sandwich cylinders under bending loads. Tests were conducted on cylinders constructed with cores weak in shear (cellular cellulose acetate) and cores strong in shear (end grain balsa) to check the validity of theoretical procedures for predicting overall buckling and wrinkling of sandwich cylinders under bending loads.

TEST PROGRAM

Test Specimens

The large number of variables which influence the behavior of a composite element such as sandwich construction require that in a test program attention be directed toward the significant parameters only. Thus, in order to study the overall buckling characteristics of sandwich cylinders, it is necessary that the sandwich thickness be as small as possible. The 1/8 inch thick sandwich used was considered to be the minimum thickness feasible. To study the wrinkling behavior of cylinders under bending loads a 1/2 inch thick sandwich was used. The nominal radius of 6 inches which was used for all cylinders was dictated by the capacity of the testing facilities. To ensure uniformity of introduction of bending load, the cylinders tested were 36 inches long.

The significant parameter in overall buckling of sandwich elements is the shear rigidity of the core material whereas the transverse elastic modulus of the core is the important parameter in wrinkling. Consequently, two different materials were selected for the core: cellular cellulose acetate (CCA) of approximately 6 lbs./cu.ft. density and end grain balsa (EGB) of approximately 5 to 5.5 lbs./cu.ft. density. For all cylinders, the face material used was 0.010 inch 24S-T3 aluminum alloy.

The cylinders used in this investigation were manufactured by Skydyne Inc. of Port Jervis, New York. The fabrication details were briefly as follows. The aluminum alloy faces were coated with a metal primer prior to assembly to the core. The core was planed

to the proper thickness and a secondary adhesive was used to bond the faces to the core. Although the adhesive used will polymerize at room temperature, sufficient heat was applied to accelerate setting of the adhesive. Pressure necessary to bring the surfaces in intimate contact was applied and the assembly was molded for a period of 2 to 3 hours.

To facilitate installation of the test specimen in the loading jig, two inch wide hardwood blocks were bonded to both the inside and outside faces at each end of the cylinder (see Figs. 1 and 3). The end faces of these blocks were then turned down on a lathe to insure planeness of the face, perpendicularity with the axis of the cylinder and parallelism of the faces.

Test Procedure

The pertinent dimensions of each specimen were determined as follows. Four evenly spaced longitudinal stations were lightly scribed on the outside wall of the cylinder. The outside radius was then measured to the nearest 0.01 inch at each pair of stations at both ends. The length of the cylinder between hardwood blocks was also determined at each station to the nearest 0.01 inch.

The total thickness of the cylinder wall was measured at each station at both ends just inside the hardwood blocks and at the center by means of a special dial gage with a least division of 0.001 inch. The thickness of the faces was measured with a ten-thousandths micrometer on samples of the face material. The average dimensions for each cylinder are given in Table 1.

Installation of the specimens in the specially designed bending loading jig was accomplished by bolting the specimen to the steel end plates through the hardwood blocks at the ends of the cylinder. The loading jig is shown in Fig. 1 with a specimen installed and tested. Load was applied by means of a hydraulic tension jack and was measured by a calibrated strain gage tension link at the jack which was accurate to ± 2 percent.

Physical Property Tests

The important physical properties in overall bending buckling of sandwich construction are the compressive stress-strain characteristics of the face material and the shear modulus of the core material. For wrinkling, the important properties are the compressive elastic moduli in each of the three planes of the core and the face characteristics.

The shear moduli of the core materials were determined by testing as simple beams, strips of flat sandwich construction. The beams were fabricated by the manufacturer of the cylinders of the same materials and in the same manner as the cylinders themselves. The test consisted of obtaining load-deflection data from which the shear modulus of the core material was determined from the difference in deflection between the experimental value and that computed for the beam neglecting shear deflections. From at least four tests of each core material, the following values of shear modulus were obtained:

cellular cellulose acetate: $\bar{G} = 3400 \text{ psi} \pm 17\%$

end grain balsa: $\bar{G} = 17,600 \text{ psi} \pm 15\%$

The compressive elastic moduli of the core was measured on 1" x 2" x 2" blocks of core material. From at least 8 tests in the direction perpendicular to the faces and 4 tests in the other two directions the values of elastic compressive moduli were as follows:

cellular cellulose acetate (CCA):

$$\bar{E}_z = 10,500 \text{ psi} \pm 16\% \text{ (perpendicular to faces)}$$

$$\bar{E}_1 = 17,700 \text{ psi} \pm 18\% \text{ (extrusion direction)}$$

$$\bar{E}_2 = 3,600 \text{ psi} \pm 25\% \text{ (transverse to extrusion direction)}$$

end grain balsa (EGB):

$$\bar{E}_z = 86,000 \text{ psi} \pm 12\% \text{ (perpendicular to faces)}$$

$$\bar{E}_1 = 14,400 \text{ psi} \pm 40\% \text{ (radial direction)}$$

$$\bar{E}_2 = 4,500 \text{ psi} \pm 20\% \text{ (circumferential direction)}$$

It is to be noted that according to data given in Ref. 1, the value of \bar{E}_z of 86,000 psi appears to be considerably lower than given therein. However, the value of \bar{E}_z obtained did correspond to that given for quipo wood which is closely related to balsa. In addition, the material tested here closely followed the description of quipo wood given in Ref. 1 as well as certain other strength characteristics. Thus, it is suspected that the core material used in the sandwich cylinders was actually quipo rather than balsa.

The with grain compressive stress-strain characteristics of the 0.010 in. 24S-T3 aluminum alloy used for the faces of the sandwich cylinders was determined by use of a solid guide compression jig of the National Bureau of Standards type. The stress-strain data are shown in Fig. 2.

Test Results

Average measured dimensions of the sandwich cylinders together with the failing loads are given in Table 1. Photographs of typical buckle patterns taken after the conclusion of the tests are shown for each type of cylinder; Fig. 3 shows a typical overall buckle pattern obtained on most of the $1/8$ in. cylinders, Fig. 4 shows a typical wrinkle for the $1/2$ in. end grain balsa cylinders and Fig. 5 shows a typical wrinkle for the $1/2$ in. cellular cellulose acetate cylinders. Additional data on the buckling and wrinkling patterns are given in Table 2. The measured wavelengths were obtained in regions of relatively little distortion.

TABLE I

Average Dimensions and Failing Loads of Sandwich Cylinders

Cylinder	Core Material	Length L	Mean Radius R	Total Thickness ($\bar{h} + t$)	Average Face Thickness t	Failing Moment M_{cr}	Maximum Failing Load/In. $N_{cr} = M_{cr}/R^2$	Maximum Failing Stress
-1	CCA	32.09"	6.48"	0.141"	0.0105"	67,900"lbs.	514 lb/in.	19,300 psi
-2	CCA	32.13	6.50	0.125	0.0105	46,100	347	16,500
-3	CCA	32.13	6.49	0.125	0.0105	77,700	587	28,000
-4	CCA	32.16	6.53	0.141	0.0105	89,600	670	31,900
-5	CCA	32.16	6.20	0.532	0.0105	92,400	764	36,400
-6	CCA	32.25	6.18	0.500	0.0105	77,700	648	30,900
-7	EGB	31.29	6.47	0.141	0.0105	53,100	404	19,300
-8	EGB	31.09	6.55	0.156	0.0105	65,700	500	23,800
-9	EGB	32.16	6.69	0.515	0.0105	82,500	588	28,000
-10	EGB	32.25	6.69	0.515	0.0105	113,300	807	38,500

TABLE 2

Data on Instability Patterns

Cylinder	Type of Instability	Location	Longitudinal	Circumferential
			Wavelength	Wavelength
			L_x	L_θ
-1 1/8" CCA	Buckle	Central	1"	3"
-2 1/8" CCA	Buckle	Central	1	3
-3 1/8" CCA	Buckle	Central	1 1/4	3 1/2
-4 1/8" CCA	Antisymmetrical Wrinkle	Both ends	7/16	πR
-5 1/2" CCA	Symmetrical Wrinkle	1" from end	1/2	1 3/4 *
-6 1/2" CCA	Symmetrical Wrinkle	1" from end	1/2	1 3/4 *
-7 1/8" EGB	Buckle	Central	1 1/4	3 1/2
-8 1/8" EGB	Antisymmetrical Wrinkle	At end	7/16	πR
-9 1/2" EGB	Symmetrical Wrinkle	Central	1/2	2 1/2 *
-10 1/2" EGB	Symmetrical Wrinkle	Central	7/16	2 1/2 *

* on inside face of cylinder only, on outside face wavelength equal πR .

CORRELATION OF THEORY WITH EXPERIMENTAL DATA

Thin Wall Cylinders

Theoretical work on buckling of a sandwich cylinder under bending loads is given in Ref. 2 for the case where the core is weak in shear. The results of this analysis indicate that for this case, the buckling load, N_{cr} , is equal to the shear rigidity of the core $\bar{h} \bar{G}$.

The 1/8 in. CCA cylinders fall into this category and, therefore, it is possible to check the theoretical work of Ref. 2 directly. The average centroidal height, \bar{h} , of cylinders -1 to -4 is 0.118 $\pm 6\%$ and the average shear modulus is 3400 psi $\pm 17\%$. Therefore, the average shear rigidity of this group of cylinders is 400 lbs./in. $\pm 23\%$ which according to Ref. 2 is the theoretical buckling loading. The average experimental failing loading was found to be 530 lbs./in. $\pm 33\%$. Thus, the experimental failing loading is 32 percent higher than the theoretical value, on the average.

In Ref. 3, comparable tests were run on sandwich cylinders under axial compressive loads. The theory of Ref. 3 indicated that the buckling loading of cylinders weak in shear is also equal to the shear rigidity of the core. For an average $\bar{h} = 0.115$ in. $\pm 7\%$ and an average shear modulus $\bar{G} = 2,000$ psi $\pm 20\%$, the average shear rigidity was 230 lbs./in. $\pm 27\%$. The average experimental failing load of eleven 1/8 in. CCA sandwich cylinders given in Ref. 3, was 235 lbs./in. $\pm 50\%$. Thus the experimental failing load was approximately 2% higher than the theoretical value, on the average, indi-

cating excellent agreement.

The fact that the bending buckling load is higher than the compressive buckling load for cylinders of the same dimensions has been observed in tests on homogeneous cylinders. It has been suggested that this behavior may be due to the buckling phenomena responding to the average value of compressive stress on the cross section rather than the maximum stress. In the case of pure bending, the maximum stress would be 1.4 times as great as the average value.

For sandwich cylinders in compression, the theory of Ref. 1 indicate that value of the parameter Et/\sqrt{GR} governs the behavior of the cylinder. Thus, it has been found that cylinders can be considered weak in shear when the value of Et/\sqrt{GR} exceeds unity. To effect a comparison between the cylinders loaded in compression and bending which were differently constructed as concerns \bar{G} and R , it appears that if the values of Et/\sqrt{GR} were equal or at least greater than unity for each group, a direct comparison would be valid.

The value of this parameter for the compression specimens averaged 5 and for the bending specimens $Et/\sqrt{GR} = 5$ also. Thus, since the compressive test data checks theory very well, it can be concluded that in bending the 32% higher experimental value is in agreement with the behavior observed for homogeneous cylinders, thus accounting for the discrepancy.

Although these conclusions are based on data with which large percentage variations are associated, it appears that the trend is clearly indicated. The fact that the scatter of the experimental

values is considerably higher than that for the core properties is based on the fact that the latter values were established from beam bending tests. In a beam test, the results are a statistical average of the core properties, whereas a structure subject to buckling responds to local weak spots caused by defects in the core properties. Thus, the scatter would tend to be greater for the buckling data.

The 1/8 in. end grain balsa cylinders, -7 and -8, can be considered to be in the weak in shear category, since for this group, $E_t/G_R = 1.4$. These cylinders, therefore, failed at a small fraction of the theoretical load. This is evidenced by the fact that the average failing loading of this group was 452 lbs./in. as compared to 530 lbs./in. for the 1/8 in. CCA cylinders, although the shear modulus of the EGB core was over five times as great as the CCA core. The fact that the EGB cylinders were not even as strong as the CCA cylinders is difficult to reconcile with the core properties. Unless some other mode of buckling is responsible for this anomalous behavior, it appears that poor bonding to the EGB core may be responsible for the seemingly low values of failing loading.

Thick Wall Cylinders

The 1/2 in. thick wall cylinders in this group were specimens -5, -6, -9 and -10, which all exhibited a symmetrical wrinkling pattern at failure as shown in Figs. 4 and 5. The theory for wrinkling of sandwich cylinders has been discussed at length in Ref. 4 from which it was concluded that the formula for wrinkling is given by

$$\sigma_{cr} = 0.65(\bar{E}\bar{E}^2)^{1/3} \quad (1)$$

$$\text{where } \bar{E} = \bar{E}_z \left(\frac{\bar{E}_x + \bar{E}_y}{2 \bar{E}_z} \right)^{1/4} \quad (2)$$

and the wavelength of the wrinkle

$$L_x = 4(\bar{E}/E)^{1/3} t \quad (3)$$

By use of Eqs. (1) to (3) and the material properties listed in this report, the following values were obtained based on an elastic modulus for the faces of $E = 10.5 \times 10^6$ psi:

cellular cellulose acetate cylinders:

$$\sigma_{cr} = 68,000 \text{ psi}$$

$$L_x = 0.42 \text{ in.}$$

end grain balsa cylinders:

$$\sigma_{cr} = 192,000 \text{ psi.}$$

$$L_x = 0.25 \text{ in.}$$

It is apparent without even correcting the above values for the effects of plasticity, that the experimental values of maximum failing stress are considerably below the predicted values. Also the predicted wavelengths are somewhat less than the observed values.

Although it is possible that the discrepancy in wrinkling stress may be due to non-linearities in the behavior of the cylinder, this effect can in all probability be ruled out on the basis that the R/t of the faces is quite large and also that the wrinkling

stresses of the CCA cylinders and EGB cylinders were substantially the same. Since the predicted value of wrinkling stress for the EGB cylinders is three times as great as that of the CCA cylinders, it appears that some other cause is responsible for the apparently poor performance of the thick-walled cylinders. One is tempted to attribute this behavior to poor bonding of the faces to the core, a difficulty frequently met in testing of sandwich structures.

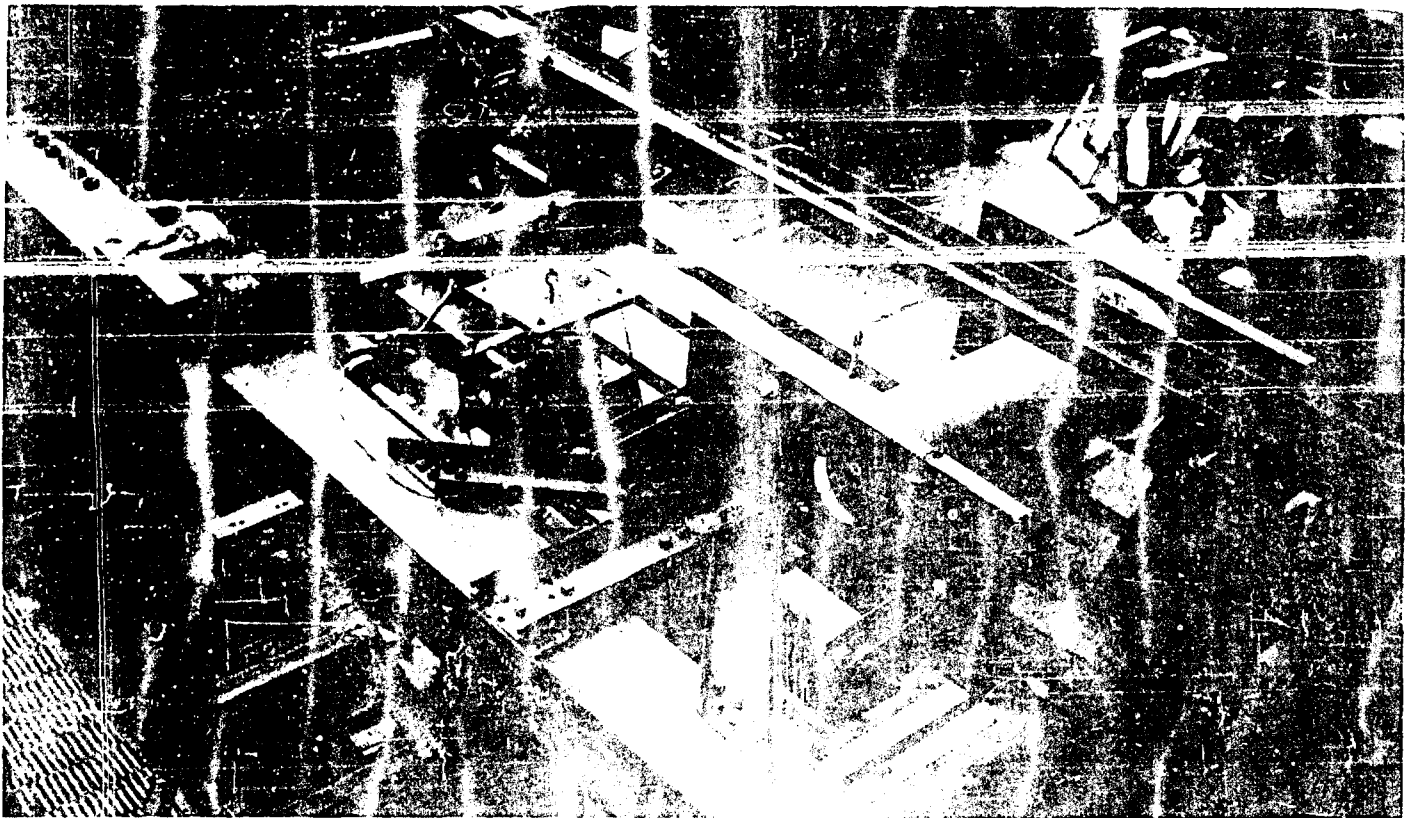
A direct comparison between the behavior of 1/2 in. EGB cylinders in bending with that in compression is afforded by the test data of Ref. 4. The cylinders tested in compression were constructed using the same density core and face material and thickness as for the group in bending. The average wrinkling stress of the cylinders which failed under compressive loading was 27,650 psi, while in bending the failing stress was 33,250 psi. Thus, the bending wrinkling stress was 1.20 times as great as that in compression, confirming the trend previously discussed.

References

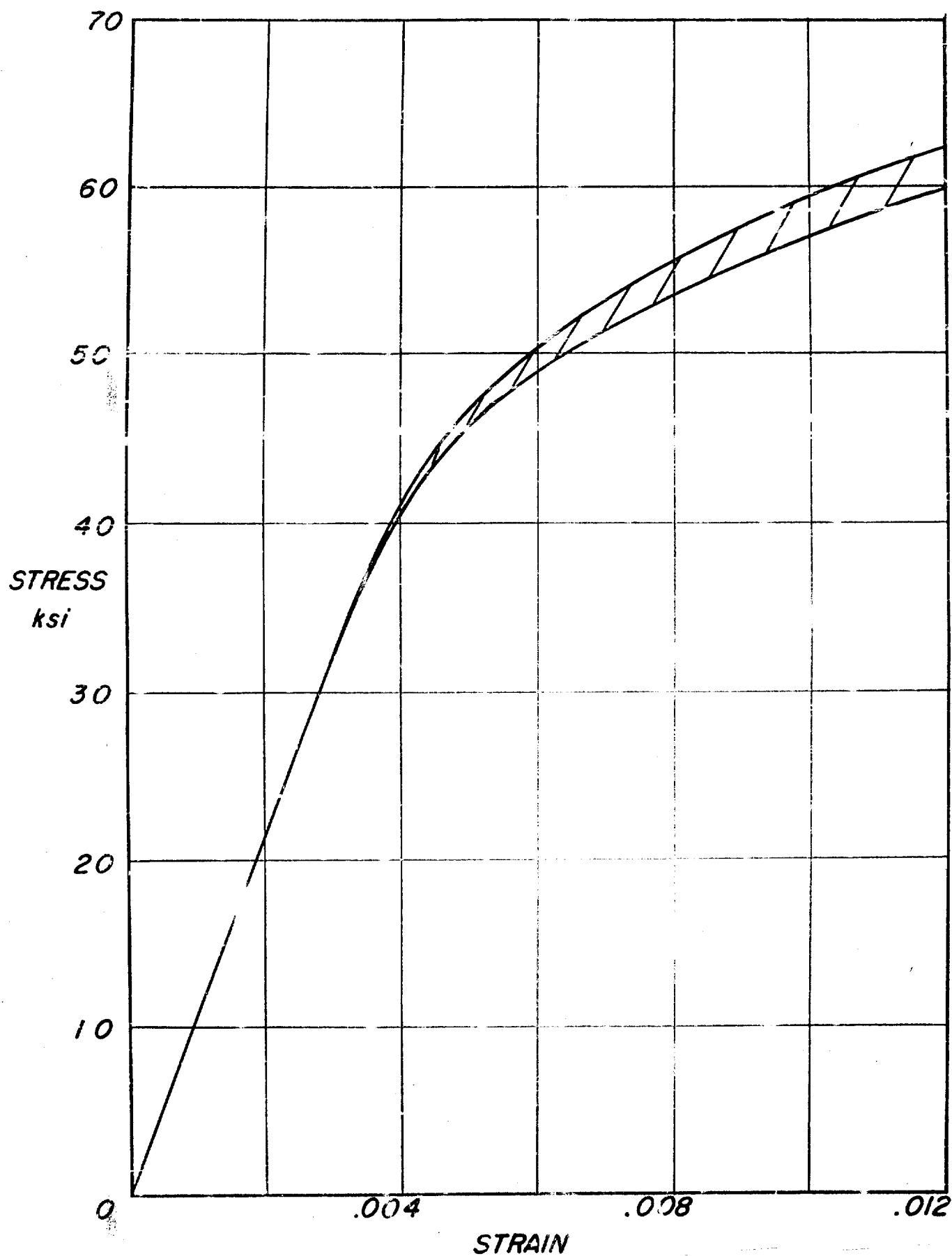
1. Wiepking, C.A. and Doyle, D.V., "Strength and Related Properties of Balsa and Quipo Woods", Forest Products Laboratory Report No. 1511, June 1944.
2. Wang, C.T. and Sullivan, D.F., "Buckling of Sandwich Cylinders Under Bending and Combined Bending and Axial Compression", Journal of the Aeronautical Sciences, Vol. 19, No. 7, pp. 468-470, 485, July 1952.
3. Teichmann, F. K., Wang, C. T., and Gerard, G., "Buckling of Sandwich Cylinders Under Axial Compression", Journal of the Aeronautical Sciences, Vol. 18, No. 6, pp. 338-406, June 1951.
4. Gerard, G., "Wrinkling Tests of Sandwich Cylinders Under Compression and Torsion Loads", New York University Report to O.N.R., October 1951.

FIGURE 1

BENDING TEST SET-UP



**FIGURE 2 COMPRESSIVE STRESS STRAIN CHARACTERISTICS
OF FACES 0.010" 24S-T WITH GRAIN**



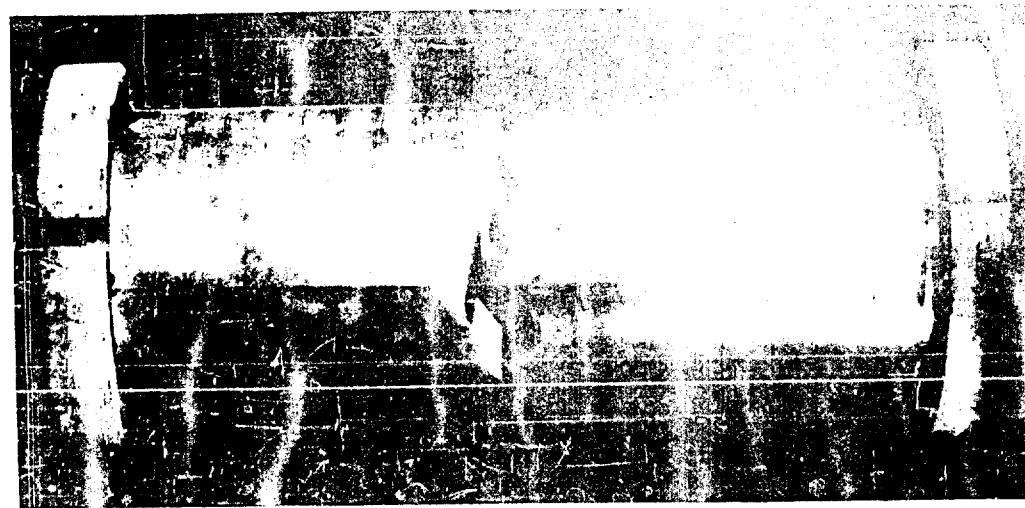


FIGURE 3
OVERALL BUCKLING
OF 118" CYLINDERS

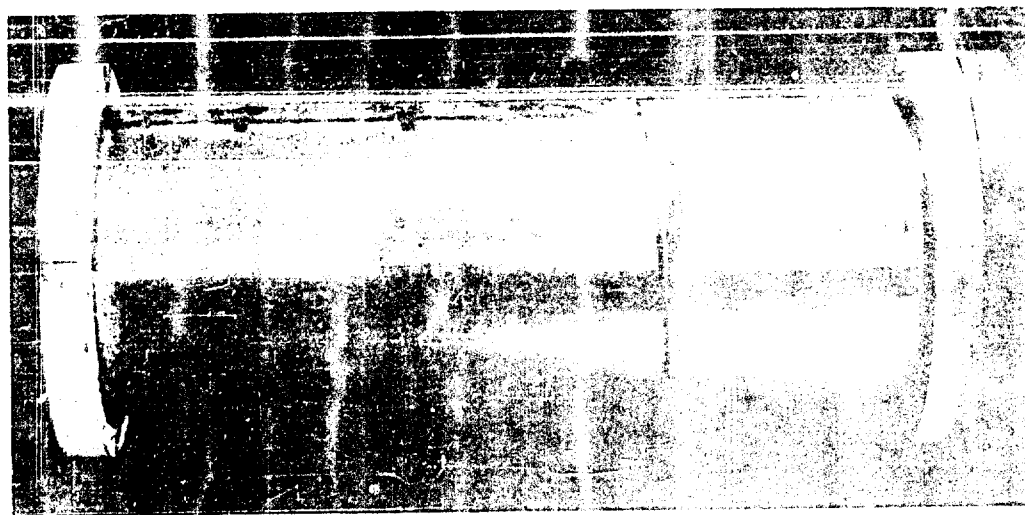


FIGURE 4
WRINKLING OF
112" EGG CYLINDERS



FIGURE 5
WRINKLING OF
112" CCA CYLINDERS